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13. ABSTRACT *(Maximum 200 words)*

The principal objective of this project is to develop a comprehensive scientific understanding of extreme floods that accounts for the dominant hydrometeorological, hydrologic and geomorphic processes at play. An important focus of this project has been on the role of basin scale for land surface and atmospheric processes that control extreme floods. Major theoretical and empirical contributions have been made in the area of hydrologic scaling. Hydrometeorological analyses have relied heavily on high-resolution radar rainfall data from the NEXRAD network of WSR-88D radars. Major contributions have been made in elucidating the structure and importance of storm systems that produce very heavy rainfall over small areas, especially in the central United States. Significant contributions have also been made at the other extreme of spatial scales through analyses of hydrometeorological processes associated with the Mississippi River Flood of 1993. Hydraulic modeling studies have been carried out to assess the dominant controls of flood wave advection and dispersion over extended stream reaches. Hydraulic studies have relied upon U.S. Army models and focused on a 20 km reach of the South Branch Potomac River. Major advances have been made in representing the control of valley floor expansions and constrictions on flow processes for very large floods. Another important contribution has been demonstration of the utility of Digital Elevation Model (DEM) data for numerical model mesh development. The research carried out under this project had not only provided improved scientific understanding of important physical processes associated with flooding, it has also enhanced the technology base available to the U.S. Army. Analyses carried out in this project utilize a wide range of emerging technologies, including remote sensing data, Geographic Information Systems, digital elevation data and advanced hydraulic models. The project has contributed to both graduate and undergraduate education with a strong focus on typically underrepresented groups in science and engineering.

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Final Report

Hydrologic Response for Regions of Diverse Physiography and Climate

Submitted To:

U. S. Army Research Office

Terrestrial Sciences Program

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Executive Summary

The principal objective of this project is to develop a comprehensive scientific understanding of extreme floods that accounts for the dominant hydrometeorological, hydrologic, hydraulic and geomorphic processes at play. An important focus of this project has been on the role of basin scale for land surface and atmospheric processes that control extreme floods. Major theoretical and empirical contributions have been made in the area of hydrologic scaling. Hydrometeorological analyses have relied heavily on high-resolution radar rainfall data from the NEXRAD network of WSR-88D radars. Major contributions have been made in elucidating the structure and importance of storm systems that produce very heavy rainfall over small areas, especially in the central United States. Significant contributions have also been made at the other extreme of spatial scales through analyses of hydrometeorological processes associated with the Mississippi River Flood of 1993. Hydraulic modeling studies have been carried out to assess the dominant controls of flood wave advection and dispersion over extended stream reaches. Hydraulic studies have relied upon U. S. Army models and focused on a 20 km reach of the South Branch Potomac River. Major advances have been made in representing the control of valley floor expansions and constrictions on flow processes for very large floods. Another important contribution has been demonstration of the utility of Digital Elevation Model (DEM) data for numerical model mesh development. The research carried out under this project has not only provided improved scientific understanding of important physical processes associated with flooding, it has also enhanced the technology base available to the U.S. Army. Analyses carried out in this project utilize a wide range of emerging technologies, including remote sensing data, Geographic Information Systems, digital elevation data and advanced hydraulic models. The project has contributed to both graduate and undergraduate education with a strong focus on typically underrepresented groups in science and engineering.

Contents

1 INTRODUCTION

This report is organized to highlight the principal research results that have been obtained under this project. As such, Section 3 - *Research Results* is the focus of the report. Section 5 contains a complete list of publications, including those that have not yet been submitted but will be submitted within the next 3-6 months. The research discussion in section 3 is designed to both emphasize the major results of the project and provide a guide for understanding the significance and interrelationships of the publications listed in Section 5.

Elements of this project should be of interest to a number of U.S. Army laboratories, in particular, the Waterways Experiment Station (WES), Hydrologic Engineering Center (HEC), Construction Engineering Research Laboratory (CERL) and the Topographic Engineering Center (TEC). Section 2 provides a brief discussion relating research results to U.S. Army mission.

2 RESEARCH RELEVANCE

Extreme flooding affects a wide range of military and civilian problems encountered by the U.S.Army. The principal military problems addressed by this research concern the interaction of fluvial processes with terrain and, in particular, problems associated with extremes of soil moisture (see DoD [1993]). Analyses carried out in this project utilize a wide range of emerging technologies, including remote sensing data, Geographic Information Systems, digital elevation model (DEM) data and advanced hydraulic models.

The Next Generation Weather Radar (NEXRAD) system of WSR-88D (Weather Surveillance Radar - 1988 Doppler) radars is a joint Department of Defense - Department of Commerce system that is intended to provide information for a wide range of forecasting and resource management problems. The NEXRAD network provides unprecedented potential for quantitative rainfall analyses at high spatial and temporal resolution and over large areas. An important element of this project has been demonstration of the utility of WSR-88D data for hydrological applications.

U.S. Army models play a central role in hydraulic and geomorphic studies (see Berger [1990], Gee et al. [1990], Deering [1990] and Richards [1990] for U.S. Army applications). In this project, hydraulic models have been utilized in settings which have received relatively little attention, i.e. modeling large floods in upland rivers over extended stream reaches. Implementation of hydraulic models has been hampered by specification of *boundary conditions*. DEM data have been utilized for hydraulic modeling in novel ways that should significantly enhance the utility of this data source, as well as the utility of hydraulic models.

3 RESEARCH RESULTS

3.1 Scale Problems

A unifying theme to the research directions pursued under the project has been examination of the role of spatial scale for hydrologic processes. Scale issues have received considerable attention in the study of terrestrial and atmospheric processes during the past decade (see Wood et al. [1990] for a review of key problems in terrestrial hydrology). Attention to scale issues turns in part on practical considerations, typically involving problems in which hydrologic variables are observed at one scale and inferences are desired at a different scale. A common situation is implementation of numerical models in which model parameters must be specified at different spatial scales from which they are measured. As many authors have noted, scale problems also lie at the heart of many of the most important fundamental scientific problems in the hydrologic sciences (see, in particular, the NRC report *Opportunities in the Hydrologic Sciences*; NRC [1990]).

Stochastic scaling models have provided a foundation for the study of scale problems in geophysics. Particular attention has been given to *simple scaling* and *multiscaling* models. Physical interpretations of scaling models are as follows. For simple scaling models, hydrologic processes are scale-invariant in the sense that processes at one scale (for example, flood peaks in a 100 km^2 basin) can be related to processes at any other scale (for example, flood peaks in a 1 km^2 basin) by a simple scale transformation. For standard multiscaling models, hydrologic fluxes result from a cascade of fluxes from large to small scale. Hydrologic processes at one scale can not be related to the same processes at a different scale simply by a characteristic scale transformation.

One of the most important theoretical results of the project is that flood magnitudes exhibit a peak in variability for basin scales ranging from 10 - 100 square miles (Smith [1992]). This feature was demonstrated using observations from the Central Appalachian region and stochastic scaling models. Figure 1 illustrates the empirical results that were used to draw inferences concerning scaling of hydrologic processes associated with extreme floods. This figure shows the relationship between coefficient of variation (i.e. the ratio of standard deviation to the mean) of maximum annual flood peaks at a site and the drainage area of the upstream basin for more than 100 central Appalachian basins.. Under simple scaling models, the CV should be constant; for standard multiscaling models the CV should decrease monotonically with drainage area, with explosive growth as drainage area decreases to 0. By contrast, figure 1 illustrates that the scaling behavior of flood peaks is qualitatively different for small basins (basins with drainage area less than 10 square miles) than for basins larger than 100 square miles. The results obtained in Smith [1992] imply that multiscaling models must be revised to account for a dominant scale.

The scaling results presented in Smith [1992] have stimulated diverse follow-up research. Gupta et al. [1994] have reproduced the scaling results for the central Appalachian region and produced similar results for other regions of the United States. Speculation on the cause of this scaling property of hydrologic processes has generated considerable attention. Gupta et al. [1994] conclude that the scaling property of flood peaks is clearly related to a *rain cell* scale, one of the principal hypotheses put forward in Smith [1992]. Smith [1992] also raises the possibility that the role of floodplains in transforming flood peaks is of major importance. This line of study is pursued under hydraulic studies which examine the role of channel and floodplain morphology in flood wave movement.

3.2 Hydrometeorological Research

The space-time structure of extreme rainstorms has been examined for the Southern Plains (Smith et al. [1994]). Characteristic modes of organization for extreme rainstorms have been identified. Some of the most important research findings concern extreme rainfall events that affect small areas, termed *isolated, locally heavy rainstorms* by Changnon and Vogel [1981] (figure 2 shows instantaneous rainfall rates obtained from the RADAP II radar at Oklahoma City at hourly intervals for a storm on June 10, 1985). The following key features of these storms have been identified:

- they are far more common in the Southern Plains than previously thought,
- they are essentially unrepresented by observations from the climatological raingage network,
- they often are made up of storms termed *chaotic convective systems* by Blanchard [1990], whose diagnostic feature is the absence of linear convective elements (see, for example, figure 2).
- topographic features often play an important role in their occurrence (see, for example, figure 3).

The June 10, 1985 storm illustrated in figure 2 resulted in point rainfall accumulations exceeding 200 mm during a period of 2-4 hours (and flash floods resulting in loss of life). Two key feature of the June 1985 storm (see Smith et al [1994]) are its slow movement (gradually backing to the southwest toward low-level moisture flow) and the organization of convection for a period significantly longer than the lifetime of a single convective cell. Maddox et al. [1979] presented a diagnostic study of storms that produced flash floods. One of the conclusions of the study is that organized convective systems are the major culprit for the large majority of documented flash floods, as opposed to isolated convective cells. Storm systems like the June 10, 1985 storm are among the smallest heavy rainfall producing storm systems in the central United States. The scale of these storm systems is likely to play a role in determining the scale behavior of flood peaks, such as the properties shown in figure 1 (see Smith [1992] and Gupta et al. [1994] for discussion of this point).

An area in which topographic features play a pronounced role in the development of *isolated, locally heavy rainstorms* is the Caprock Escarpment region of the Texas panhandle. Figure 3 illustrates the initiation and development of convective systems along the Caprock Escarpment. The observations are taken from hourly accumulation products from the Lubbock WSR-88D site on June 6, 1994. The interactions among land surface and atmospheric processes, such as those exhibited in the Texas panhandle, are of particular importance for both civilian and military problems associated with heavy rainfall. With the advent of the WSR-88D network of radars, rapid advances should occur in characterizing regional rainfall regimes. As characteristic patterns of rainfall are related to land surface features, rapid advances should also occur in characterizing land surface processes related to soil moisture.

Analyses of extreme rainfall on a much larger scale were undertaken as part of this project due to the unique opportunities provided by the Mississippi River flood of 1993. Hydrometeorological analyses of the storms resulting in the Mississippi River flood of 1993 have provided a fascinating example of extreme hydrometeorological processes over the largest of continental scales (Bradley et al. [1993, 1994], Bradley and Smith [1994] and Smith et al. [1994]). The analyses point to some very unusual features of the storm systems as well as to some very common features.

Many of the storms that produced the Mississippi River floods exhibited very common life cycles for central US storms. Afternoon thunderstorms were generated to the lee of the Rockies in Colorado and Nebraska (often associated with orographic circulations). These thunderstorms tracked over the the central United States under the influence of upper level steering winds and developed into large rainfall producing storms as they passed along the Kansas - Nebraska border into Iowa and Missouri (figure 4 shows total rainfall for June and July of 1993). Two features of these storms were, however, very unusual: 1) the frequency of occurrence (from June 15 - July 15, organized thunderstorms developed on all but 2 days), and 2) the frequency of storms that developed over the central plains into heavy rainfall producing storms.

Figure 5 illustrates the spatial structure of a storm that produced point rainfall accumulations exceeding 150 mm during a period of 2-4 hours on July 13-14 of 1993 (based on composite WSR-88D radar rainfall estimates from 9 radars in the central US). Very heavy local rainfall, as well as flash floods, were common during June and

July 1993. Heavy regional rainfall during the two-month period resulted from storms like the July 13-14 storm which produced locally heavy rainfall.

Water budget analyses for the period of the Mississippi flood point to record atmospheric water vapor convergence over the region as a distinctive feature of the event (figure 6a). Atmospheric water budgets were carried out for the domain represented by the box in figure 4 using humidity and wind data from twice-a-day operational radiosonde sites and daily rain gage data. Figure 6a contains a scatterplot of monthly moisture convergence for a 17 year period ending in 1992. June and July months are distinguished from other months and the June 15 - July 15, 1993 value of moisture convergence is plotted separately. The 140 mm convergence is more than twice as large as the previous record during June and July.

Figure 6b shows a scatterplot of monthly precipitation and precipitation recycling ratio, which is defined as the fraction of precipitation resulting from locally evaporated water. Recent studies have suggested that precipitation recycling provides a significant land surface feedback to the atmosphere (see Brubaker et al. [1993]). The results of Bradley et al. [1994a] indicate that precipitation recycling was at near record low levels during the summer of 1993 and that precipitation recycling is not a significant feedback mechanism linking atmospheric and land surface processes. Additional analyses suggest, however, that elevated soil moisture may have augmented convective activity in the area of heaviest rainfall by increasing convective instability (the so-called *Betts mechanism*; Betts et al. [1994]). This mechanism may partially explain the high frequency of storms that developed over the central US into heavy rainfall producing events.

Storm-event analyses are being carried out using full volume scan WSR-88D radar data. (Smith et al. [1994a] and [1994b]). Figure 7 shows Dodge City WSR-88D reflectivity data from the 0.5 degree tilt for the July 14 event. The figure depicts the southwest end of the line of convection shown in figure 5. Rainfall accumulations of more than 150 mm during the period 0 - 2 UTC on July 1 resulted from a period in which the storm appears to remain stationary with heaviest rainfall along the southwest flank. Figure 7 illustrates some of the key features involved. During the period, new cells repeatedly formed in the same location. A density front (shown in figure 7 as a reflectivity thin line) appears to organize convective development near the area of heaviest rainfall accumulation. A key element of research involving WSR-88D data is development of procedures for quantitative water budget analyses of extreme storm events.

3.3 Hydrologic Research

Numerical experiments have been carried out using hydrologic models for small experimental watersheds in the central Appalachian region (Troch et al. [1993] and [1994]). These experiments were designed to examine the relative importance of land surface and atmospheric processes for flood production. Specifically, the objectives of these experiments were to assess the importance of intial soil moisture conditions, runoff production mechanisms (and in particular saturation excess and infiltration excess mechanisms), and rainfall rate variability for flood production in a humid central Appalachian setting. The most important conclusions of this research are the following:

- initial soil moisture conditions exert significant control on hydrologic response, even for very large floods,
- *saturation excess* runoff dominates *infiltration excess* runoff for most flood events in the central Appalachian region. Even for very large floods, such as the flood produced by Hurricane Agnes in 1972, saturation excess runoff contributions may exceed infiltration excess contribution.

The numerical experiments utilized a topographically driven hydrologic model in the TOPMODEL family, initially developed by Beven and Kirkby [1979]. This family of models has become a community standard and has broad utility for terrain problems involving topographically controlled soil moisture distribution. The model used in this study represents both infiltration excess runoff production (that is, runoff production resulting from conditions in which rainfall rate exceeds infiltration capacity) and saturation excess runoff production (that is, runoff production for conditions in which the soil column becomes saturated). Numerical experiments are carried out for a 4 km^2 research watershed in the Mahantango Creek, a Valley and Ridge basin of Pennsylvania. High resolution rain gage and stream gage data are available from the experimental watershed and served as the basis for model analyses.

Figure 8 summarizes numerical experiments, which were carried out for the 12 largest flood events during a 10 year period of observation. The first panel illustrates that *model-derived* saturation excess dominates infiltration excess. The second panel illustrates that for the largest flood magnitudes, initial soil moisture condition (represented in the figure by a scaled initial storage capacity), plays an important role. The third panel shows the sensitivity of peak runoff to peak rainfall intensity.

The study presented in Troch et al. [1994] is a unique example of implementing a sophisticated numerical model for real watersheds to examine tightly posed hypotheses concerning dominant hydrologic processes for extreme flood events. The study will have lasting importance both for the specific results and in providing a paradigm for combining hydrologic experimentation and numerical modeling.

Determination of dominant runoff production mechanisms plays an important role in water quality analyses due to different flow paths associated with saturation excess runoff and infiltration excess runoff. Basin scale contaminant transport has been examined in the context of runoff processes (Sturdevant and Smith [1994]). One of the important results obtained in Sturdevant and Smith [1994] is that large floods in the Potomac River basin are dominant events in terms of nutrient transport (see figure 9). Total phosphorus concentration is shown in figure 9 to increase significantly for very large floods. The largest flood during the period of record, which occurred in November 1985 in association with hurricane Juan, produced total P concentrations more than twice the previous record. Further study of basin scale contaminant transport in association with large floods is one of the major areas of follow-on research from this project.

3.4 Hydraulic and Geomorphic Research

Research has been carried out on hydraulic controls of flood peaks, with the objective of determining the dominant channel and floodplain controls of flood peak magnitudes and flood wave movement. Numerical studies of channel and floodplain controls of extreme floods in the Central Appalachian region have been carried out using 1-D and 2-D open channel flow models (see Chung et al. [1993], Mas et al. [1994], Miller et al. [1994a and b] and Chung [1994]). Research has centered around RMA-2V, a finite element code for the 2-D shallow water equations. This code was developed for, and has been extensively used by WES.

The most important results of this research are the following:

- the alternating sequence of valley floor contractions and expansions in central Appalachian basins exerts a pronounced control on advection and dispersion of flood waves, especially for very large floods,
- 2-D open channel flow models, and in particular RMA-2V, are capable of representing important flow processes for flood wave movement and transport processes in high-gradient central Appalachian streams,
- DEM data have the potential for significantly enhancing the applicability of 2-D models through improvements in mesh development.

Numerical models have been implemented for a 20 km reach of the South Branch Potomac River, near Petersburg, West Virginia. Figure 10 illustrates topography of the *Petersburg reach* in which a broad floodplain is bounded by pronounced constrictions at topographically controlled gaps. Figure 10 is constructed from 30 meter USGS DEM data using the GRASS GIS (see Mitasova [1993] for discussion of GIS applications within CERL). A unique feature of this research is implementation of 2-D flow models for high-gradient upland environments. Most applications of RMA-2V have been in low-gradient environments, and in particular coastal and estuarine environments. Bates et al. [1992] and Gee et al. [1990] discuss implementation for riverine environments, but not for large floods in high-gradient environments.

Implementation of RMA-2V for the Petersburg reach was based on detailed cross-sections developed by the U.S. Army Corps of Engineers, 30 meter DEM data, and surveyed cross-sections that were obtained during field work in October, 1993. Attention has focused on the November, 1985 flood in the South Branch Potomac River. The November 1985 flood is the flood of record in the South Branch Potomac River.

High-water marks and aerial photography (before and after event, showing erosional and depositional features) are available for model validation. Figure 11 illustrates the model velocity field for the November 5, 1985 flood peak in the Petersburg floodplain. High water marks are accurately represented as are flow processes corresponding to principal erosional and depositional features

Figure 12 illustrates a RMA-2V solution that was part of a unique set of experiments in which the finite element mesh was generated solely using USGS 30 meter DEM data. In Mas et al. [1994a and 1994b] and Mas [1994], the utility of DEM data for mesh generation is examined in detail. It is concluded that DEM data can be of particular utility for study of flow processes associated with very large floods in high-gradient environments.

The valley floor constrictions and expansions illustrated in figure 10 for the Petersburg flood plain are associated with bedrock-controlled gaps. Similar features also occur in association with debris deposits associated with high-gradient tributary streams. These features are common throughout the central Appalachian region and in other high-gradient basins (see Kieffer [1990] for dramatic examples from the Colorado River basin). Numerical experiments were carried out to examine flow processes for a stream reach upstream of Petersburg in which debris deposits provided pronounced channel-floodplain constrictions, at least up until November 5, 1985. Unlike bedrock-controlled constrictions, tributary debris deposits may be reworked by ensuing large floods, providing both large sediment supply and altered boundary conditions for subsequent events.

Figure 13 illustrate hydraulic changes in channel/floodplain system with before and after flow analyses for Redman Run reach (see Miller et al. [1994]). The two solutions are both for peak flow during the 1985 flood. The pre-flood solution is based on a mesh created from pre-flood topographic maps and aerial photographs. The post-flood solution is based on surveyed cross-sections following the 1985 flood. A tree-covered bar in the middle of the section was completely stripped of vegetation by the flood. A debris deposit at the downstream end of the reach was completely scoured by the flood. Figure 14 shows two pre-flood solutions, one in which trees are represented and a second in which floodplain roughness parameterization does not account for the presence of trees. The results presented in Miller et al. [1994a] and illustrated in figures 13 and 14 highlight the difficulties in hydraulic and contaminant transport modeling for extreme flood events.

3.5 Soil Erosion

Soil erosion involves the range of hydrometeorological, hydrologic and hydraulic processes examined in this study in the context of space-time variability of atmospheric land surface processes. An important result was obtained under this study that bears upon problems of soil erosion, namely that radar can potentially provide accurate measurements of the driving process of soil erosion, rainfall kinetic energy flux.

The relationship between rainfall rate, radar reflectivity factor (the quantity measured by weather radar) and rainfall kinetic energy flux were examined from a theoretical and experimental perspective in Smith and De Veaux [1992]. Standard assessments of rainfall kinetic energy flux used for soil erosion studies rely upon hourly (or longer time interval) rain gage data. The networks from which these assessments can be made are typically very sparse, relative to the 1 - 4 km sampling resolution of radar.

Smith and De Veaux [1992] show that radar measurements of rainfall kinetic energy flux are potentially more accurate than gage measurements and provide supporting experimental evidence to support this result (figure 15). Similar studies have recently been carried out at the Technical University (ETH) in Zurich with very similar results (Steiner [1992]). The national network of weather radars provided by the NEXRAD system thus provides the potential for marked advances in observational, experimental and ultimately management advances in the field of soil erosion.

4 EDUCATION

Over the duration of the project, three graduate students have been supported and contributed to the project. One student, Wei-hao Chung, completed his PhD dissertation *Open Channel Flow Modeling of Large Floods* during the summer of 1994.

A second graduate student, Diane M. L. Mas, will defend her MS thesis *2-D Open Channel Flow Modeling for the South Branch Potomac River* during the fall of 1994. A third graduate student, Paula L. Sturdevant, has begun dissertation research on contaminant transport processes for large floods.

Two undergraduate students, Lucinda Shih and Bess Mah, have worked as research assistants for the project. Both students have assisted in diverse research areas of the project, gaining experience in GIS, remote sensing, and numerical modeling. Lucinda Shih is currently working on a senior thesis concerning sediment transport in the South Branch Potomac River. She will work with U.S. Army hydraulic models as a component of her research. She will also carry out field work needed for model implementation.

Research from this project has been incorporated into undergraduate and graduate courses taught at Princeton by J. A. Smith. U.S. Army models are used for computational laboratories in a junior-senior level course on *Environmental Fluid Mechanics.* WSR-88D data and analyses are used in a graduate course on *Hydrometeorology.*

5 PUBLICATIONS

This section summarizes publications that have resulted from the project. The section is divided into two parts, the first containing publications that have appeared or are already in press. The second section lists manuscripts that result from research under this project that will be submitted for publication within the next 3 months. In the first section, we include published abstracts only for papers that have not yet been published (i.e. papers that appear in the following subsection).

5.1 In Press

Bradley, A. A., J. A. Smith and M. L. Baeck, Hydroclimatology of the 1993 rainstorms in the Mississippi River basin, EOS, 74(43), 62, (Abstract), 1993.

Bradley, A. A., J. A. Smith and M. L. Baeck, Rainfall patterns and hydrometeorological conditions associated with rainstorms during the 1993 Midwest floods, EOS, 75(16), p. 170, (Abstract), 1994.

Chung, W.-H., Open Channel Flow Modeling of Large Floods, Ph.D. Dissertation, Princeton University, 1994.

Chung, W.-H. and J. A. Smith, Modified method of characteristics procedures for flood routing, submitted to Advances in Water Resources.

Chung, W.-H. and J. A. Smith, The linearized Saint Venant equations, submitted to Hydrological Sciences Journal.

Chung, W.-H., A. A. Aldama, and J. A. Smith, On the effects of downstream boundary conditions on diffusive flood routing, Advances in Water Resources, 16, 259 - 275, 1993.

Mas, D.L., A. J. Miller, J. A. Smith, and W. Chung, Analysis of levee design in a mountain river using two-dimensional flow modeling, Proceedings of the 1994 National Conference on Hydraulic Engineering, Buffalo, New York, in press.

Miller, A.J., Mas, D.L., Chung, W.-h., and Smith, J.A., 1994a, Boundary conditions and flow patterns in a mountain river: Proceedings of the 1994 National Conference on Hydraulic Engineering, Buffalo, New York, in press.

Miller, A.J., Mas, D.M.L., Smith, J.A., and Chung, W.-H., 1994b, Changes in flow pattern associated with channel and floodplain erosion in mountain valleys: EOS, Transactions, American Geophysical Union, v.75, p.182.

Smith, J. A., A. A. Bradley, and M. L. Baeck, The space-time structure of extreme storm rainfall in the Southern Plains, Journal of Applied Meteorology, December 1994.

Smith, J. A., Representation of basin scale in flood peak distributions, Water Resources Research, 28(11), 2993 - 2999, 1992.

Smith, J. A. and R. D. De Veaux, The temporal and spatial variability of rainfall power, Environmetrics, 3(1), 29 - 53, 1992.

Smith, J. A., W. Zhao, and A. A. Bradley, Water vapor flux studies for extreme rainfall events, Chapman Conference on Water Vapor in the Climate System, October, 1994, in press.

Sturdevant, P. L. and J. A. Smith, Sediment and nutrient transport by large floods in the Potomac River basin, EOS, 75(16), p. 165 (Abstract), 1994.

Troch, P. A., M. Mancini, C. Paniconi and E. F. Wood, Evaluation of a distributed catchment scale water balance model, Water Resources Research, 29(6), 1805 - 1817, 1993.

Troch, P. A., J. A. Smith, E. F. Wood, and F. O. de Troch, Hydrologic controls of large floods in small basin: central Appalachian case study, Journal of Hydrology, 156, 285 - 309, 1994.

5.2 In Preparation

Bradley, A. A. and J. A. Smith, Hydroclimatology of the 1993 rainstorms in the Mississippi River basin, in preparation for Water Resources Research.

Chung, W.-H. and J. A. Smith, A random-coefficient advection-diffusion equation for flood routing, in preparation for Stochastic Hydrology and Hydraulics.

Mas, D. L., 2-D Open Channel Flow Modeling for the South Branch Potomac River, M. S. thesis, Princeton University, 1994.

Mas, D. L., J. A. Smith, and A. J. Miller, Use of DEM data for 2-D hydraulic

modeling, in preparation for Water Resources Research.

Smith, J. A., W. Zhao, and A. A. Bradley, Radar studies of extreme storms during the Mississippi River Flood of 1993, in preparation for Water Resources Research.

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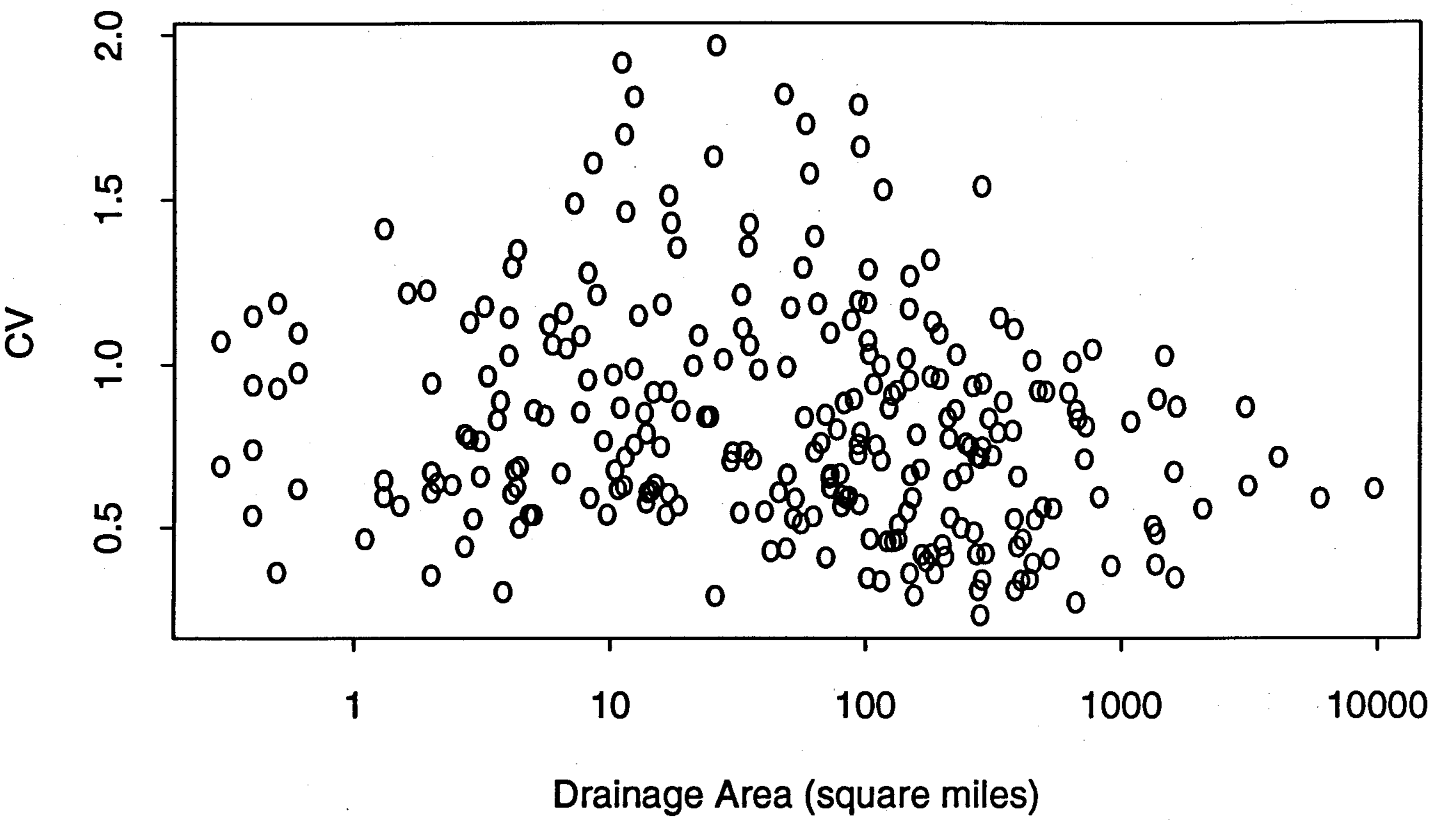


Figure 1. Coefficient of variation of annual flood peaks for 104 central Appalachain drainage basins.

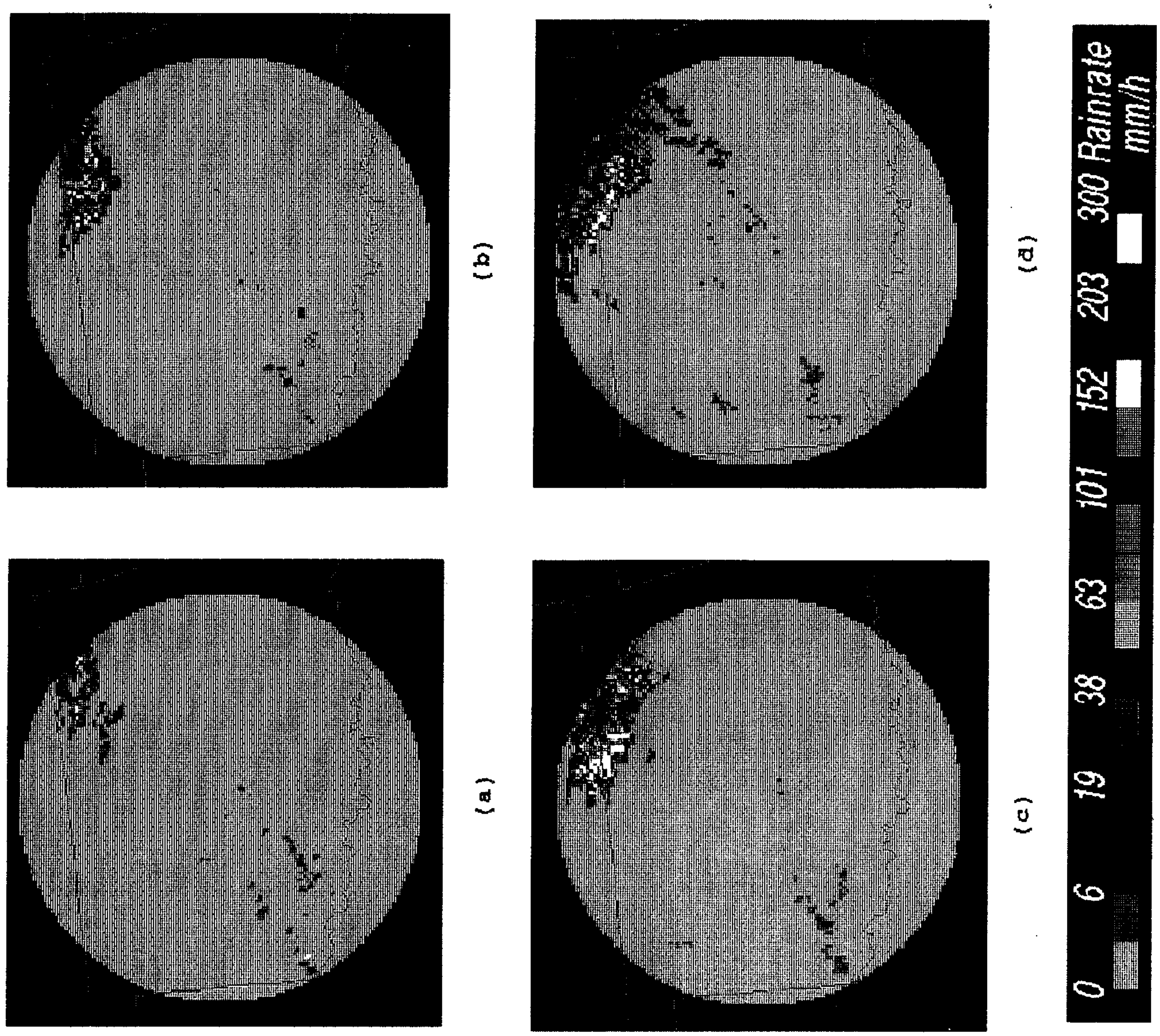


Figure 2. Radar estimates of rainfall rate (mm/h) from the Oklahoma City WSR-57 radar for a storm on June 10, 1985. Images are separated by 1 hour.

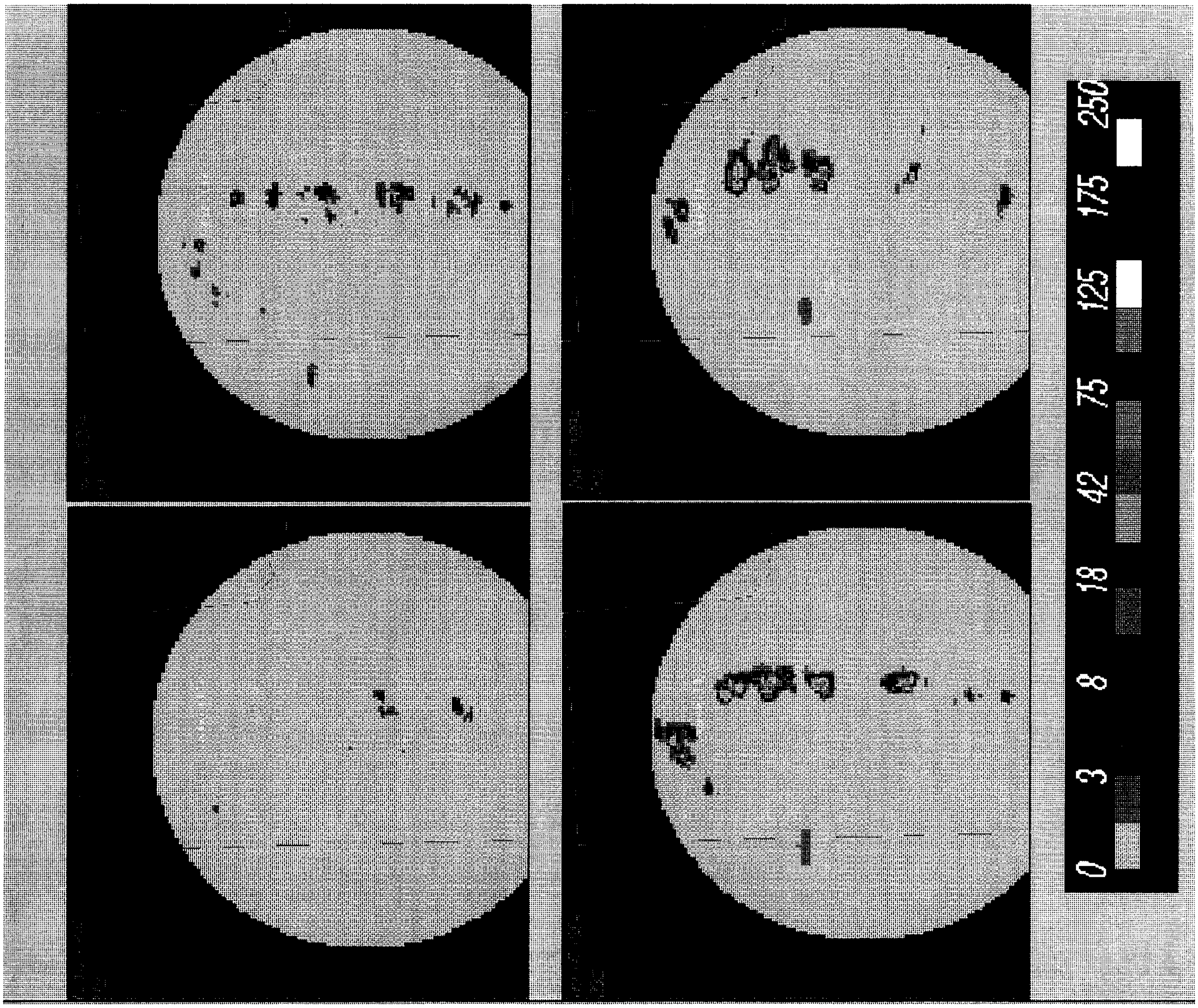


Figure 3. Hourly rainfall accumulation fields from the Lubbock WSR-88D for June 6, 1994 (in mm).

Mid-June to Mid-July 1993

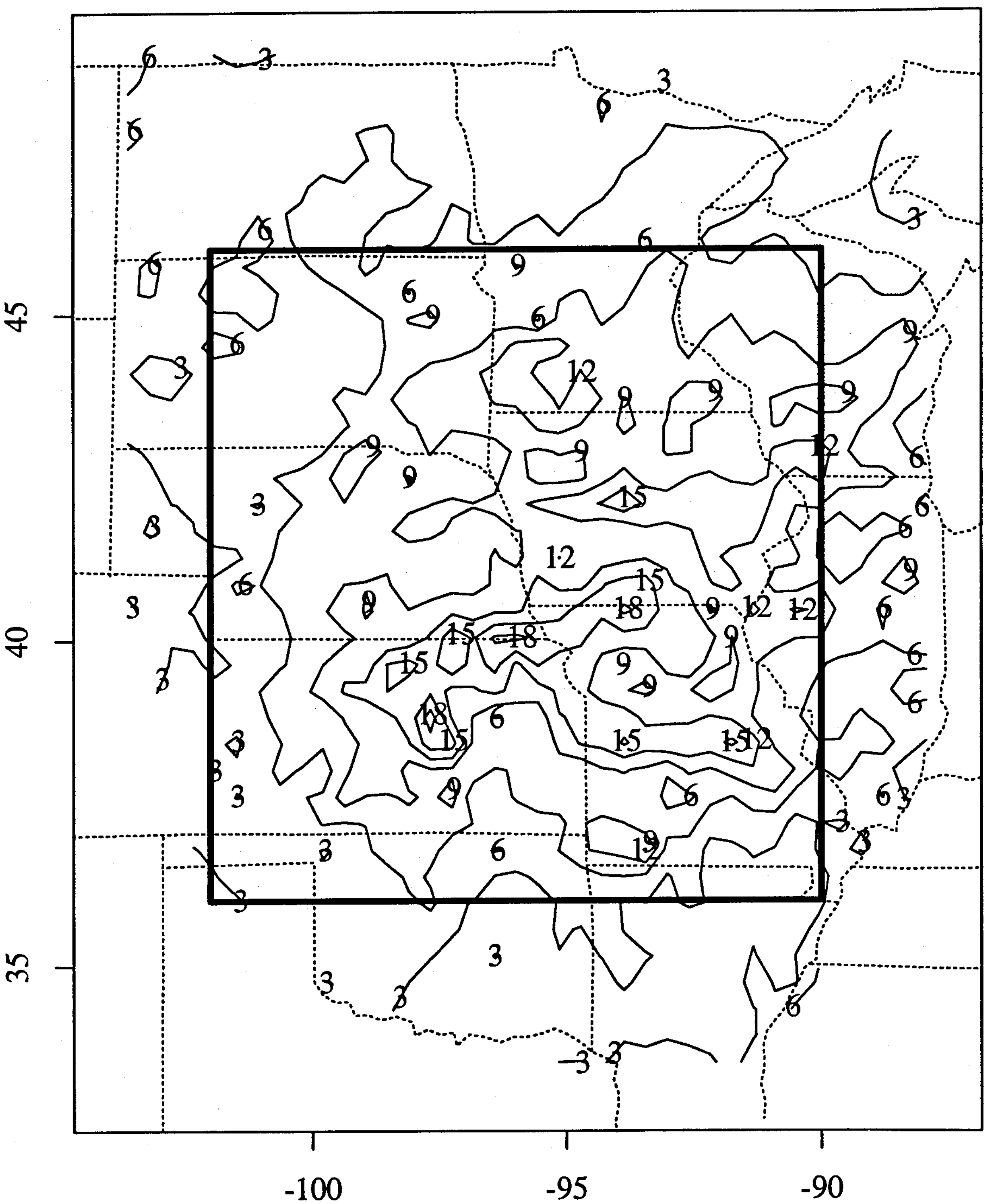


Figure 4. June 15 - July 15, 1993 rainfall accumulation in inches.

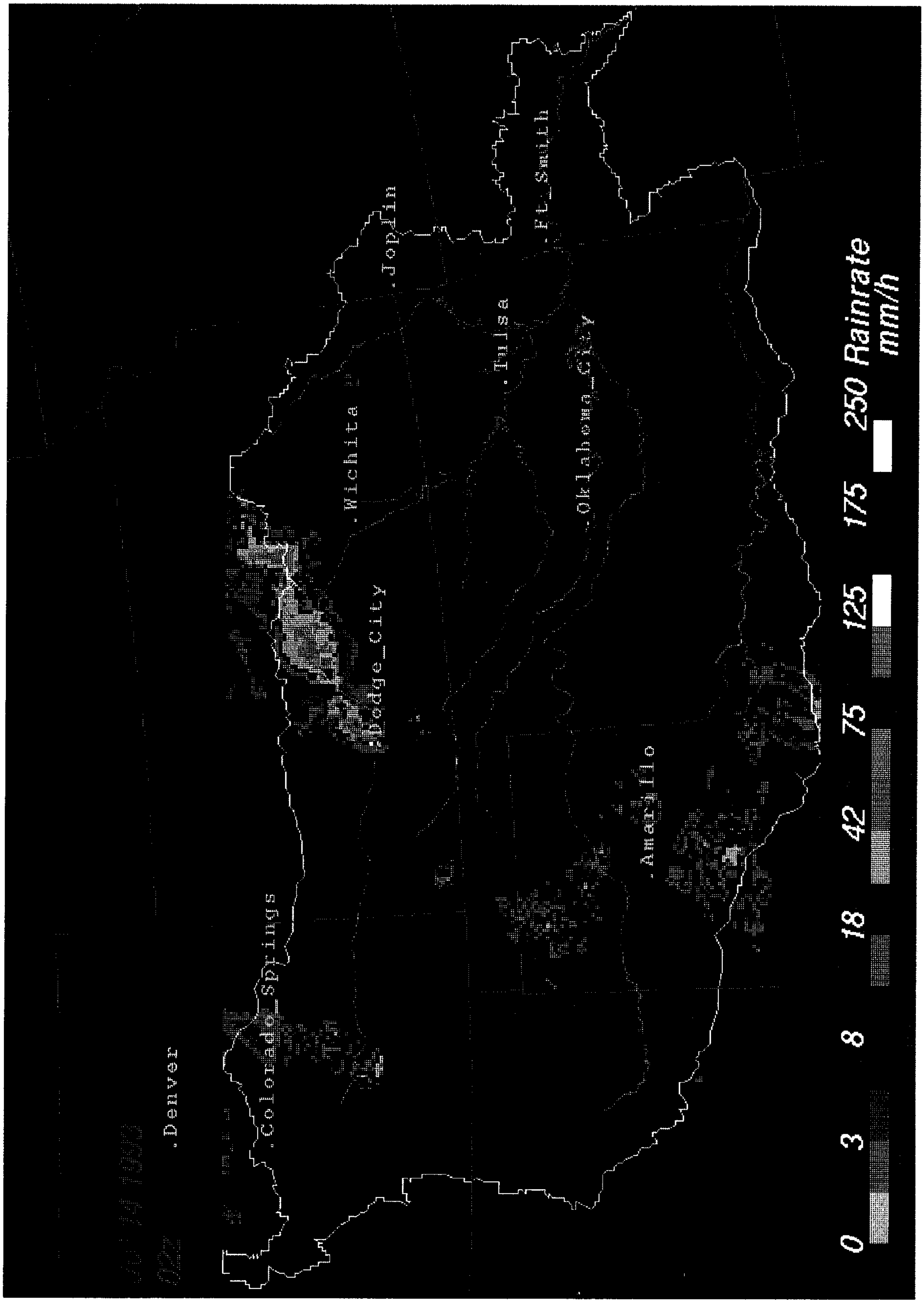


Figure 5. Hourly rainfall accumulation for July 14, 1993 2 UTC from 9 Southern Plains WSR-88D sites.

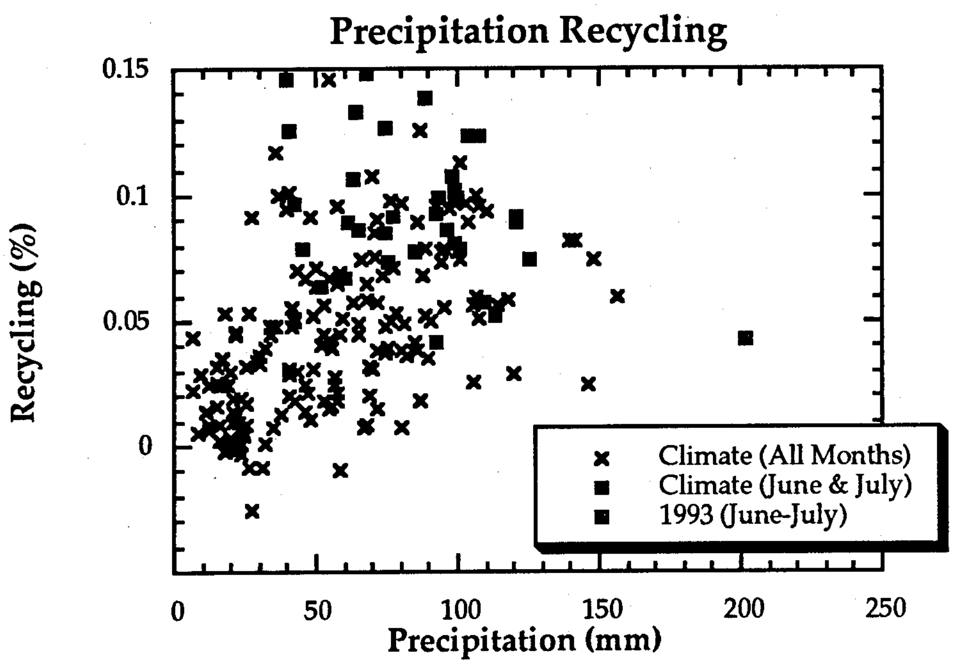


Figure 6b Precipitation recycling estimates for the Mississippi flood region.

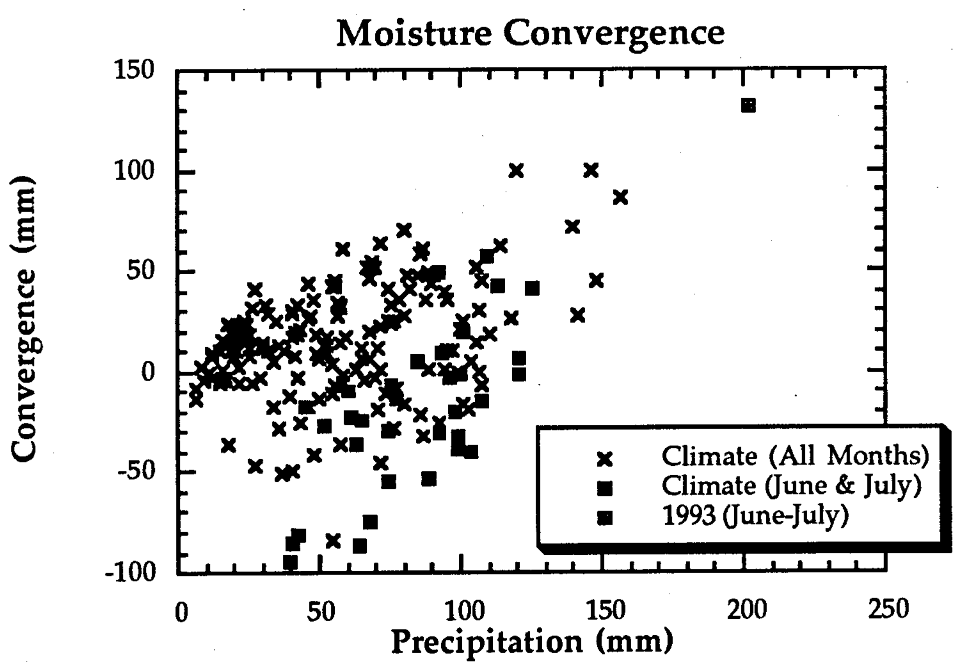


Figure 6a Moisture convergence estimates for the Mississippi flood region.

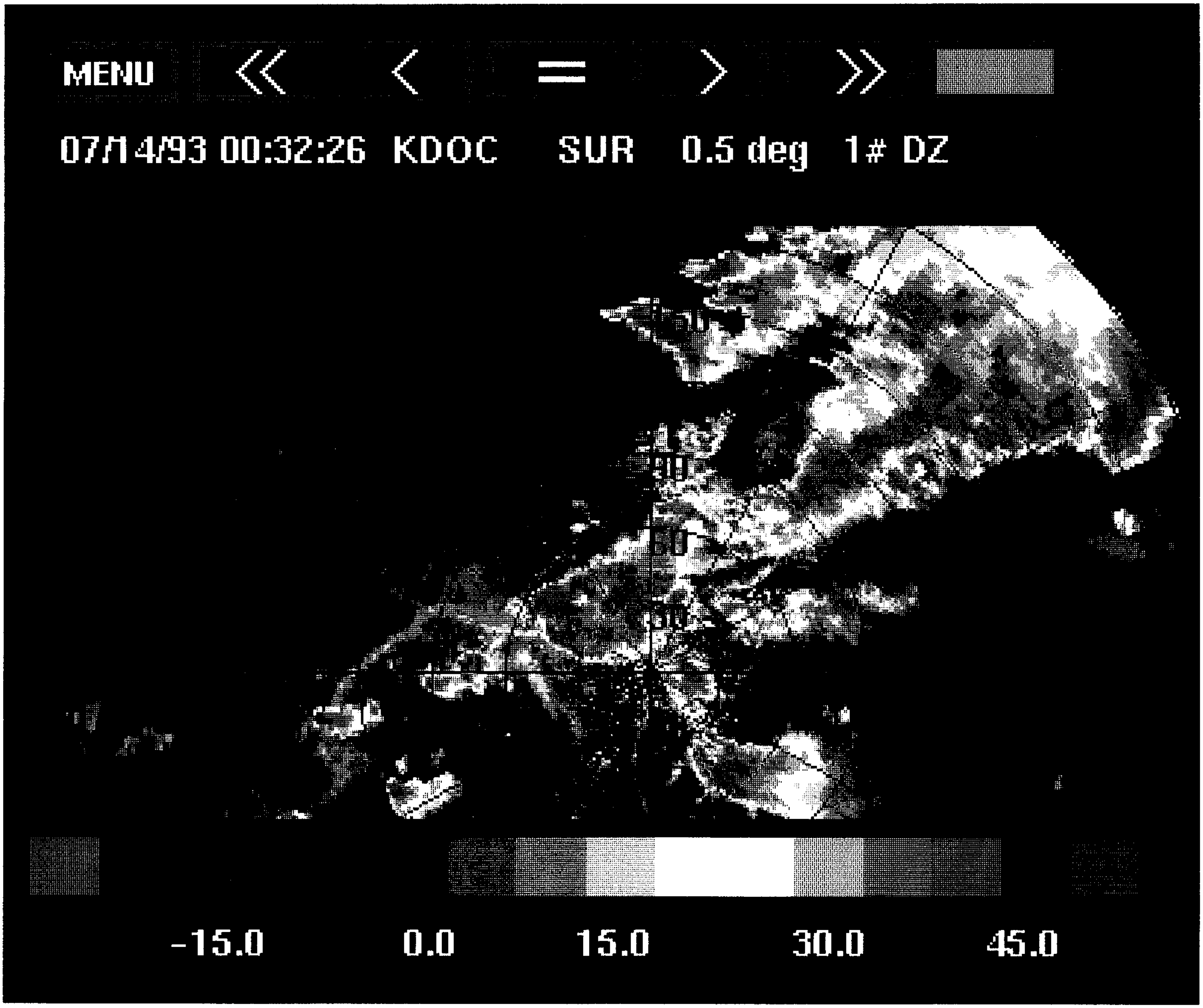
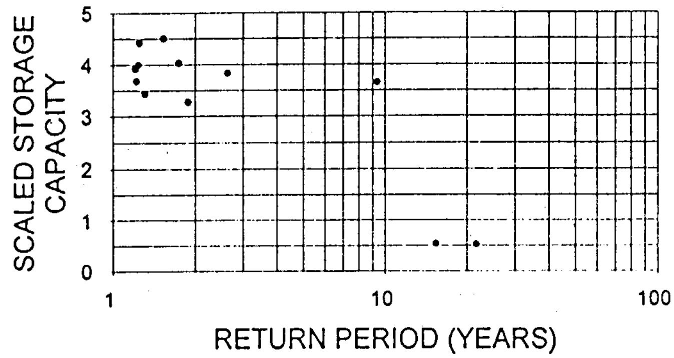
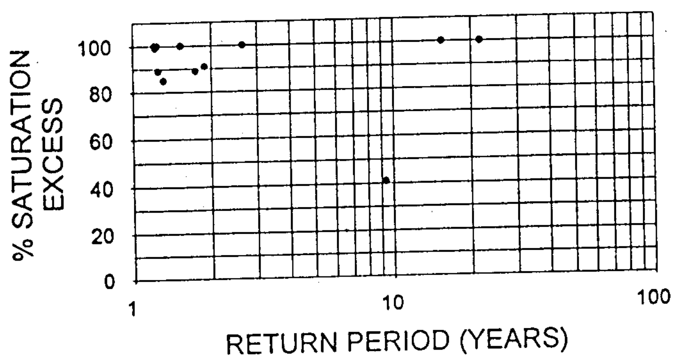


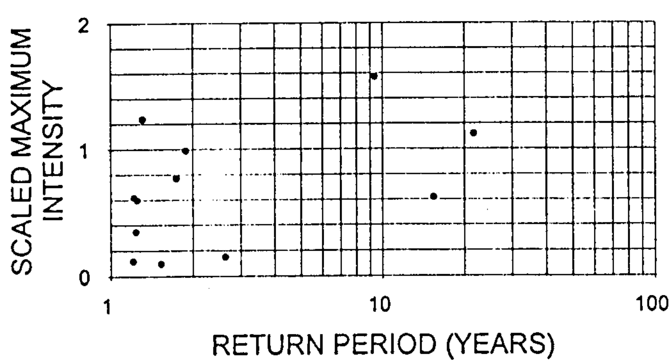
Figure 7. Base reflectivity (in dBZ) from the Dodge City WSR-88D for July 14, 1993 1 UTC.



Scaled initial storage capacity vs. flood return period.



Percentage of saturation excess runoff production vs. flood return period.



Scaled maximum intensity vs. flood return period.

Figure 8. Hydrologic model results for 12 flood events in the Mahantango watershed, Pennsylvania.

Figure 9b Time series plot of total phosphorus concentrations for the Potomac River, Washington, D.C. (USGS NASQAN site).

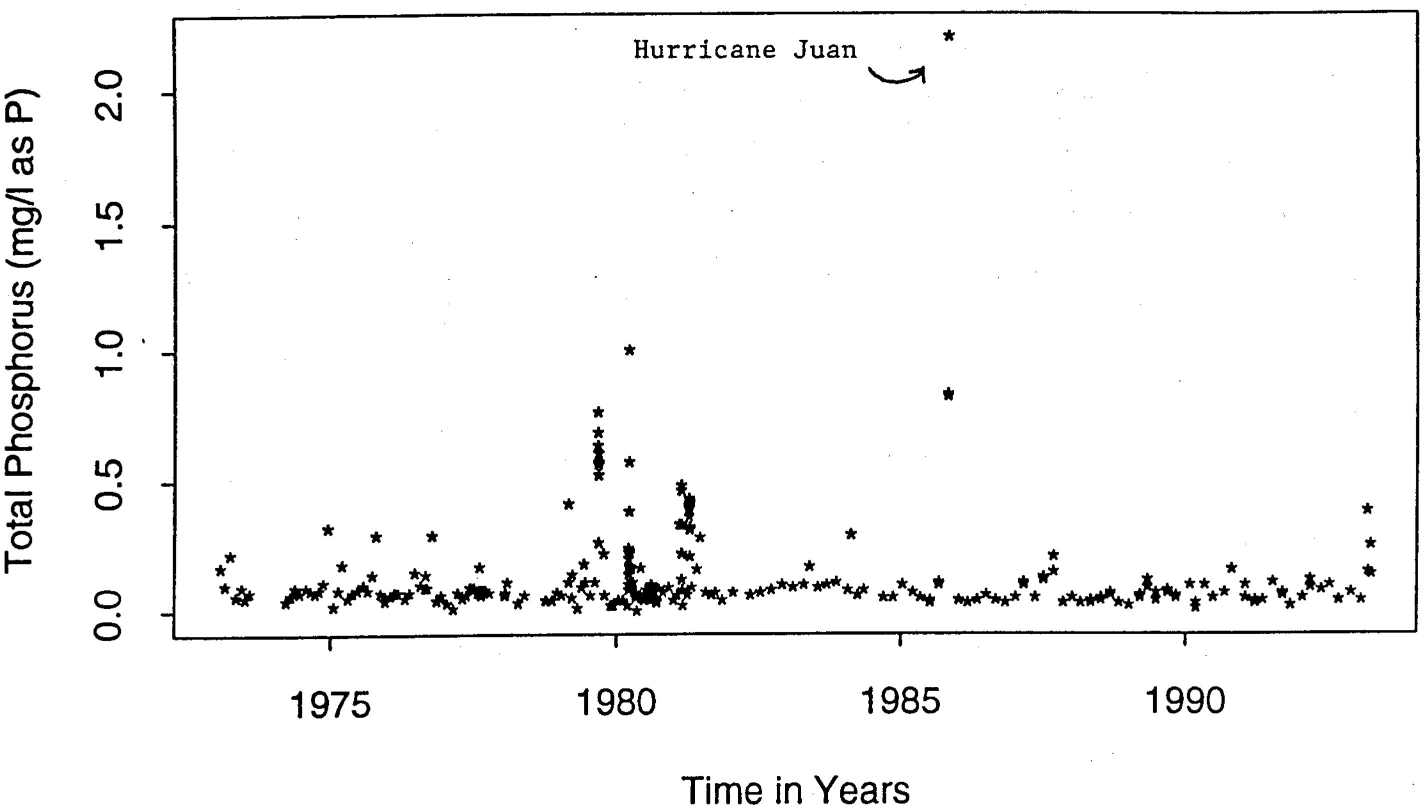
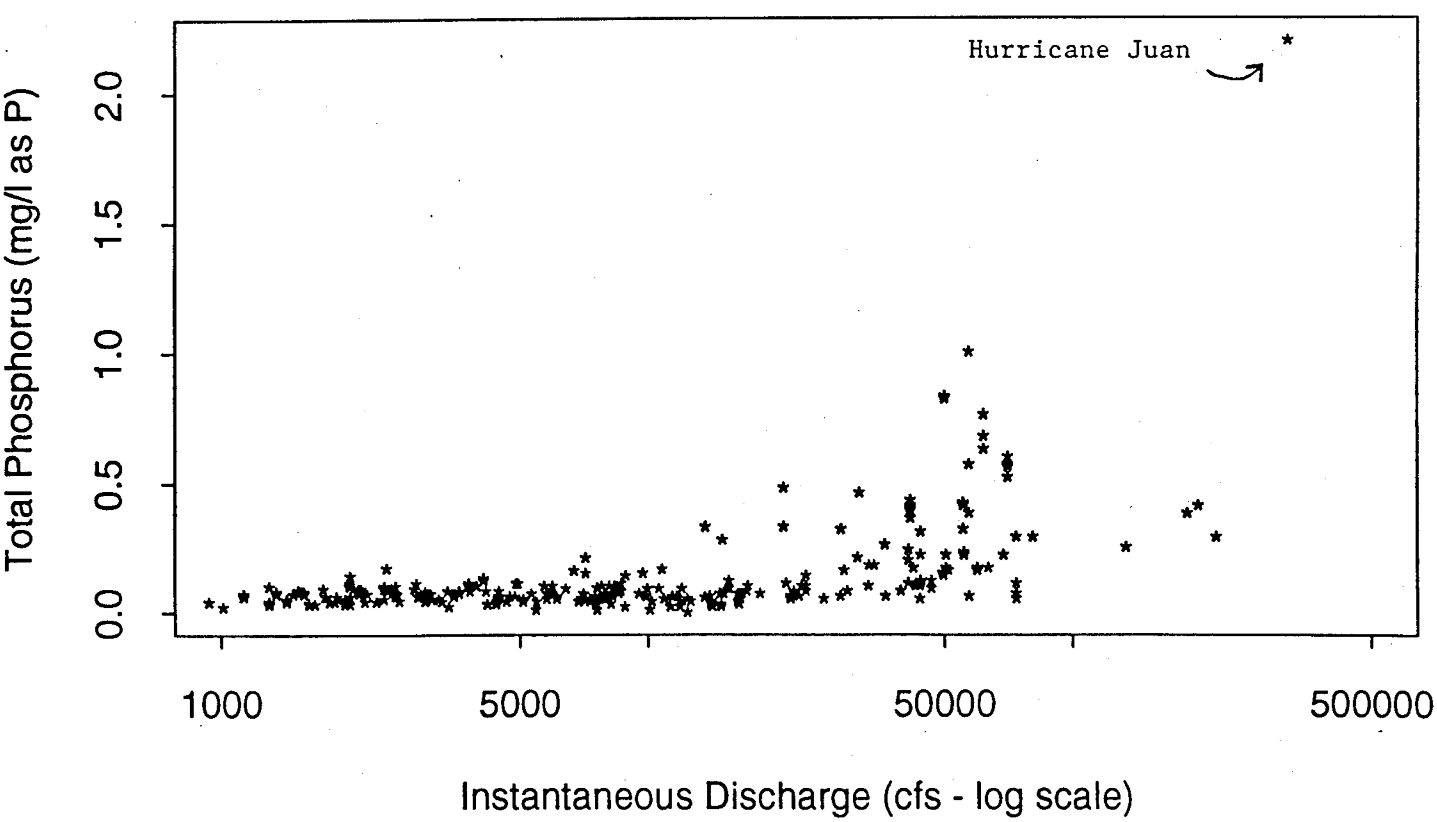


Figure 9a Scatterplot of Potomac River discharge and total phosphorus concentration (1974 - 1992).



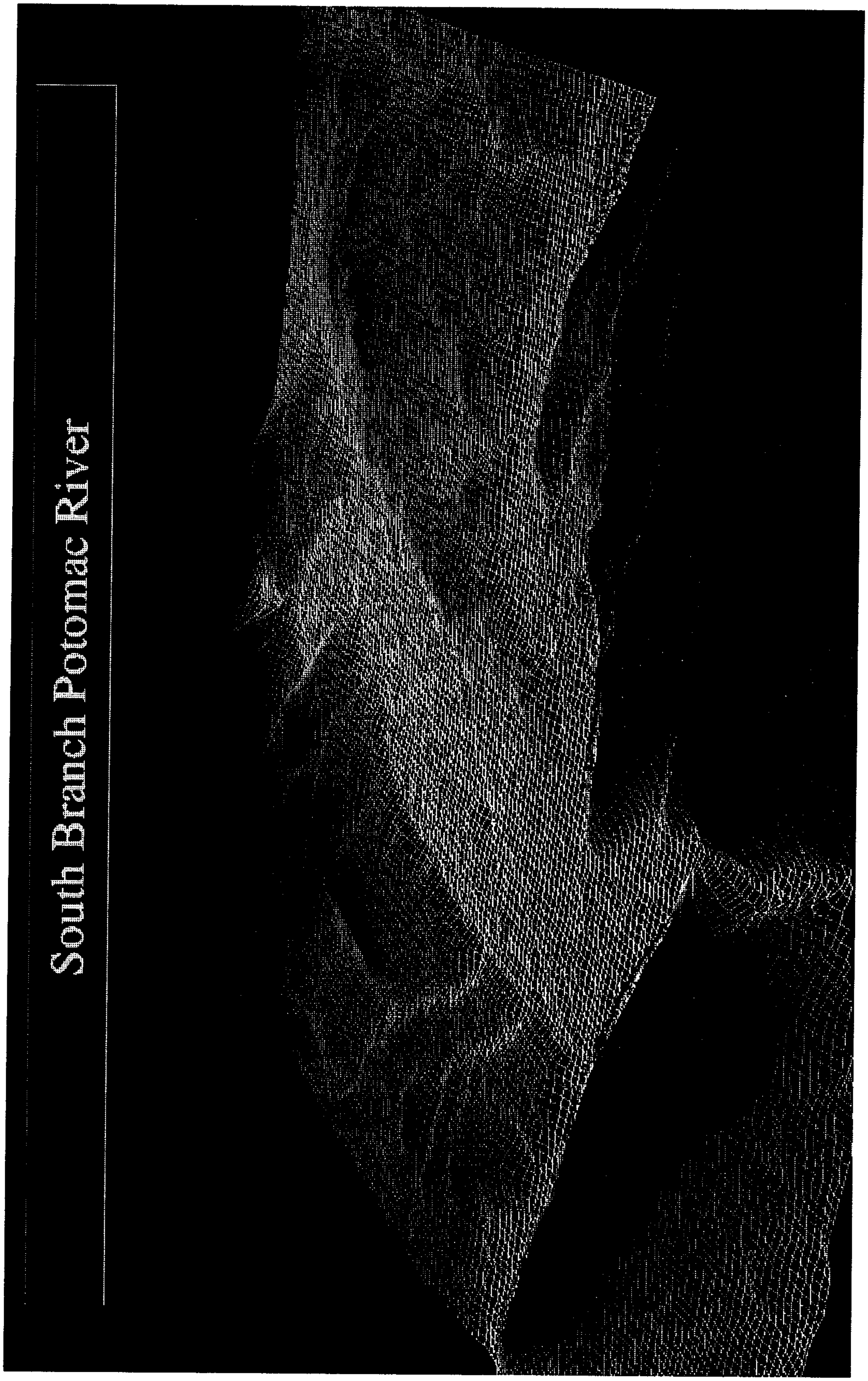


Figure 10. DEM-derived topography for the Petersburg floodplain and surrounding region.

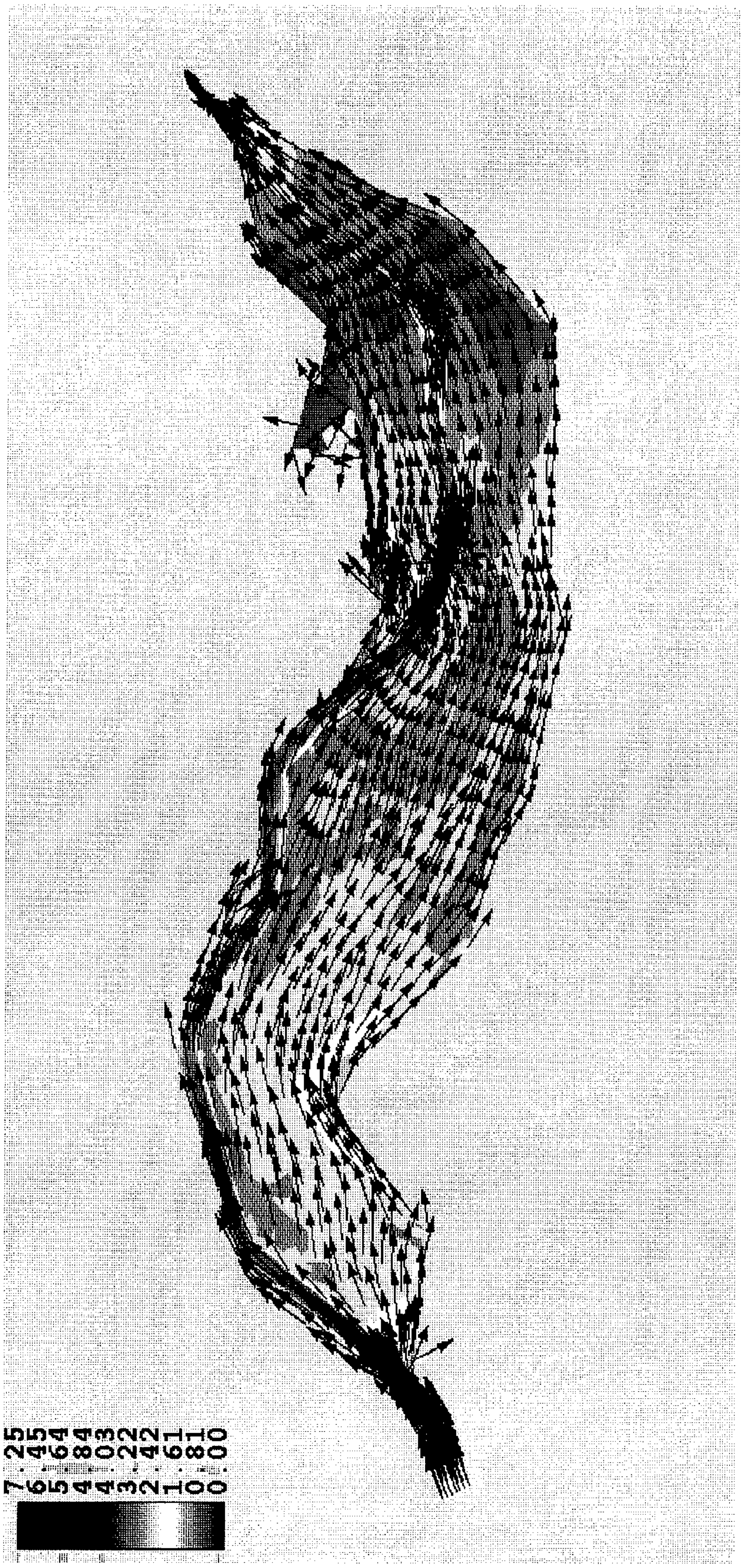


Figure 11. RMA-2V results for the November 1985 flood in the Petersburg floodplain.

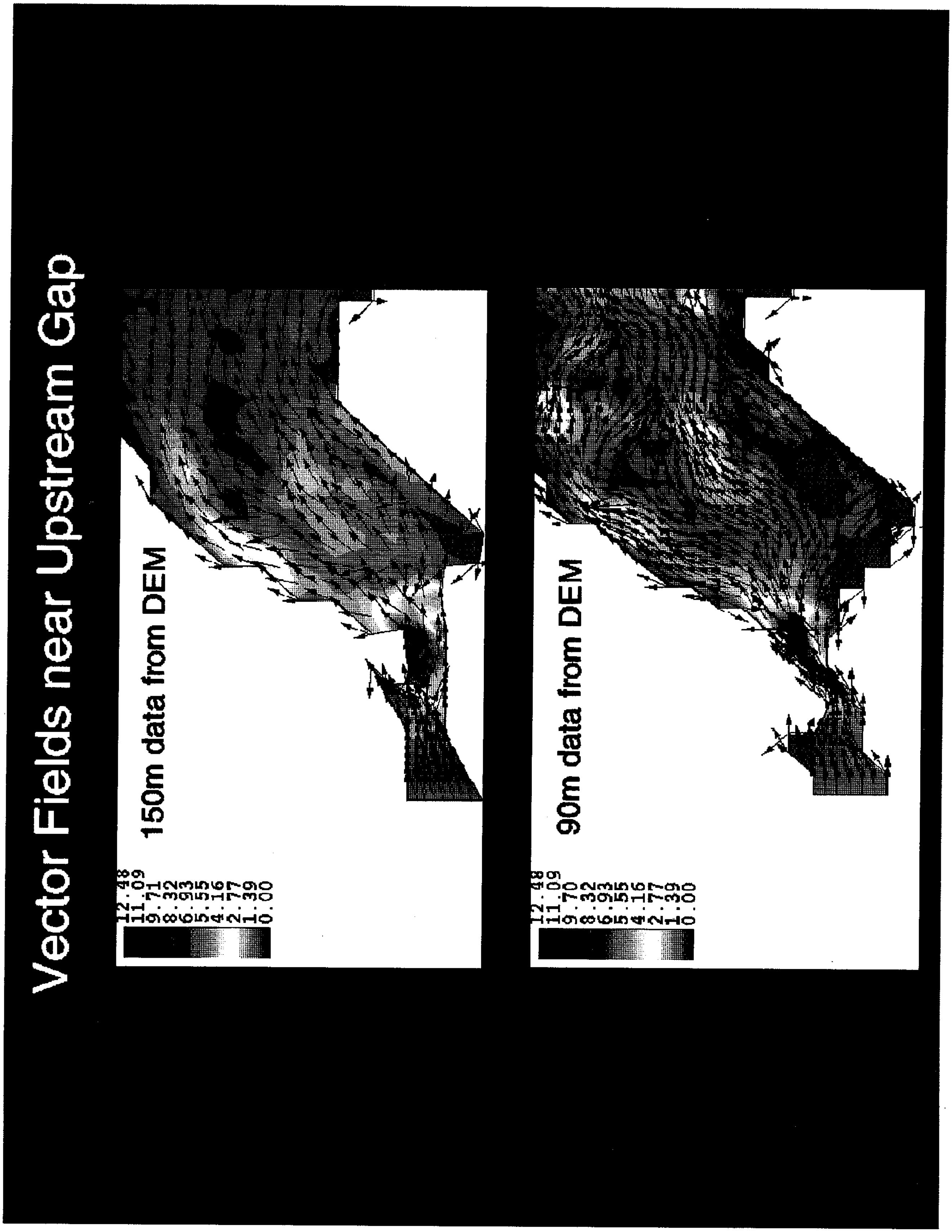


Figure 12. RMA-2V results for DEM-derived meshes.

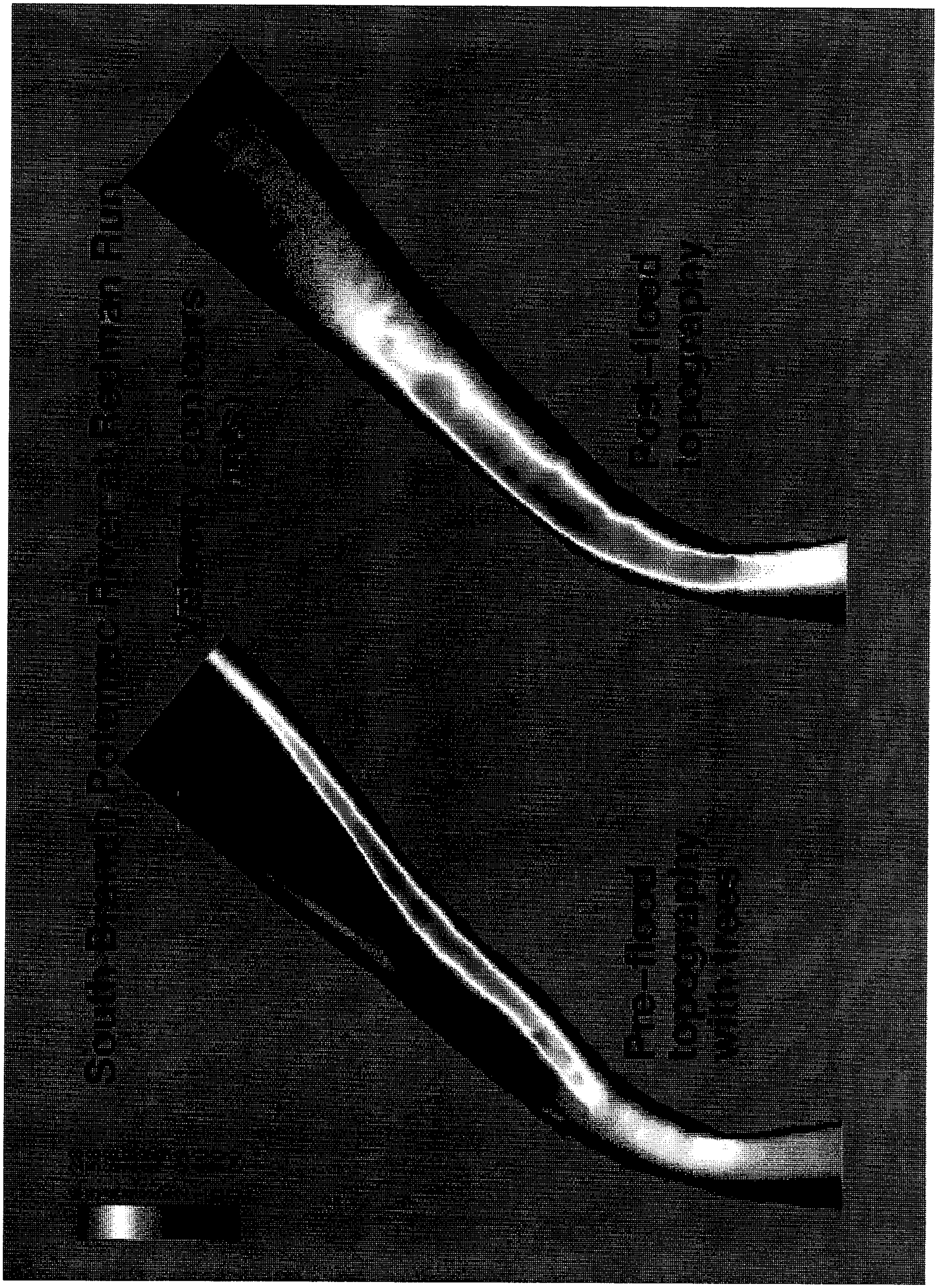


Figure 13. RMA-2V results for pre-flood and post-flood meshes in the Redman Run reach.

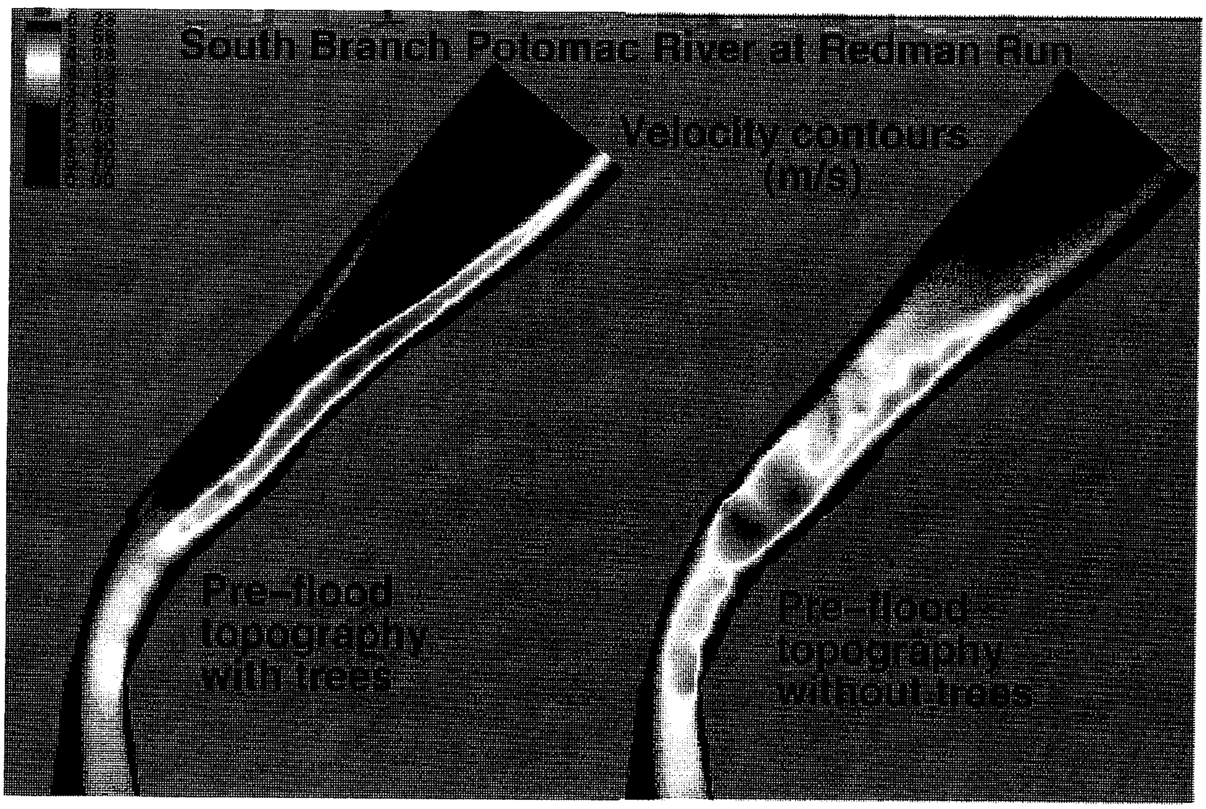


Figure 14. RMA-2V results for Redman Run reach under different roughness parameterizations.